# TECHNO-ECONOMIC ANALYSIS OF AN OFF-GRID MICRO-HYDROKINETIC RIVER SYSTEM FOR REMOTE RURAL ELECTRIFICATION

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## Abstract

This study investigates the use of off-grid micro-hydrokinetic river system as a cost-effective and sustainable electricity supply option for remote rural residents in close proximity to flowing water and not having access to grid electricity. This hydrokinetic technology is still in the development stage and there is a lack of application especially in rural areas with reasonable water resource. This study will present the economic and environmental benefits of the proposed system. A mathematical model is developed to simulate the system performance as submitted to different solicitations. A test prototype will also be used in order to validate the simulation results.

Keywords: hydrokinetic river system, rural electrification, System Modelling, techno-economic analysis, test prototype.

## 1. INTRODUCTION

### 1.1 Greenhouse gases and reduction strategies

The demand for energy is constantly rising while the availability of fossil fuels is constantly declining [1]. High costs of fossil fuels and carbon emissions will make investment in renewable energy more cost-effective. These days, due to international policies and concerns on environmental issues, the importance of generating electricity by means of renewable energy sources has increased [2]. Concentration of greenhouse gases (GHGs) in the atmosphere causes changes in the global climate. These changes will have severe environmental, economic and social impacts over the coming decades [3]. To prevent GHGs from rising to a dangerous level, Kyoto Protocol (1997) was established as an agreement which industrialises countries to reduce their combined greenhouse gas emissions by at least 5% during period 2008 to 2012 [3] . South Africa acceded to the Kyoto protocol in March 2002. A new five-year second commitment period under Kyoto protocol started running from 1 January 2013 and will conclude on 31 December 2017.

According to the environmental statistics, South Africa is among top 20 countries in the world with high emission level of carbon dioxide [4]. It is by far the largest emitter of GHG in Africa due its energy intensive, fossil-fuel powered economy. South African electricity price has increased substantially to fund the new capacity being built.

Due to Eskom bulk tariff increase to municipality, National Energy Regulator of South Africa (NERSA) had set guideline increase of 15.33% for 2010/11, 16.03% for 2011/12 and 16.16% for 2012/13 by municipalities [5]. In 2010, the South African national department of energy released the Integrated Resources Plan (IRP) of increasing its target for electricity production from renewable energy sources to 17.8 GW (mainly from wind, solar, biomass and small scale hydro) by 2030 [6]. In the medium term, 3.725 GW will be procured for commissioning by 2016. South African government has embarked in setting strategies encouraging sustainable energy development and energy use through efficient practices.

## 1.2 Rural electrification techniques

Despite the efforts in remote area electrification, progress and success rates remain low. Poor planning, lack of research and negligence are some of the factors hindering the rural electrification deployment [7]. Remote communities often require electricity for small loads such as lighting, refrigeration, communications etc. [8]. Solution towards rural electrification is made possible by means of basic approaches/techniques such as grid-extension, diesel generators or small scale renewable energy systems [9]. However, grid-extension to rural areas is considered uneconomical by many utility companies, due to the low consumption and poor load factors. This is certainly an unattractive supply option since most rural residents in developing countries are poor and thus unable to finance electrical services [10]. Also due to electrical tariff increase, this is an unsustainable solution for poor rural communities.

The utilization of diesel-power generators (DG) and small-scale renewable generation sources such as photovoltaic, hydro, wind and bio-mass in rural areas compensates grid-extension. DG has been the most popular option since it used to be the cheapest available option, particularly for low load applications [11]. It can be used in many remote settlements, either for a single user or as part of a local distribution network. In addition, it is easy to install and easy to operate. Nevertheless, DG approach continues to be more unsustainable for rural residents due to further increase of petroleum prices and difficulties in transporting the fuel to other remote areas.

## 1.3 Renewable energy sources

Among different renewable energy technologies, hydropower generation (large and small scale) holds prime position in terms of contribution to the world's electricity generation [12, 13, 14 & 16]. In remote areas with access to moving water, traditional hydropower is the most cost-effective, reliable and environmentally-sound mean of providing electric power [12]. Nevertheless, large-scale traditional hydropower stations are equipped with large dams and huge water storage reservoirs. As a result they received considerable criticism due to their negative environmental impact [13-15].

Some remote areas are situated in close proximity to rivers having little or no alleviation at all. Hence, it is impossible to deploy conventional micro-hydro generation [16]. The only possible solution to deploy is micro-hydrokinetic river (MHR) technology. Hence, this shows that hydrokinetic river technology can work over a much wider range of sites than those of traditional hydropower generation [17].

## 1.4 Hydrokinetic technology

This hydrokinetic technology is a new category of hydropower generation. It is immature and still in the development stage. It becomes more attractive among other renewable energy sources due to its high energy density, good predictability and minimal environmental impact [18-20]. To generate electricity, it utilizes the kinetic energy of flowing water instead of potential energy of falling water. Hence, it generates electricity without the construction of dams and other costly projects [21-24].

Figure 1 shows an outline of off-grid hydrokinetic energy conversion system. Hydrokinetic energy is captured from waves, tides, ocean currents, the natural flow of water in rivers, or marine thermal gradients [25 & 26]. However, the scope of this work is limited to the application in free-flowing rivers only, since it is suitable for small-scale electricity generation [17 & 27]. Definition of small, mini and micro hydro plants available in current literature are presented in Table 1. Micro hydropower is more appropriate for the residential use. Anything greater would be simply wasteful.

Table 1: Small scale hydropower classification by power generation

| Classification | Size in KW |
|---|---|
| Small hydro | 1,000 - 30,000 |
| Mini hydro | 100 - 1,000 |
| Micro hydro | < 100 |

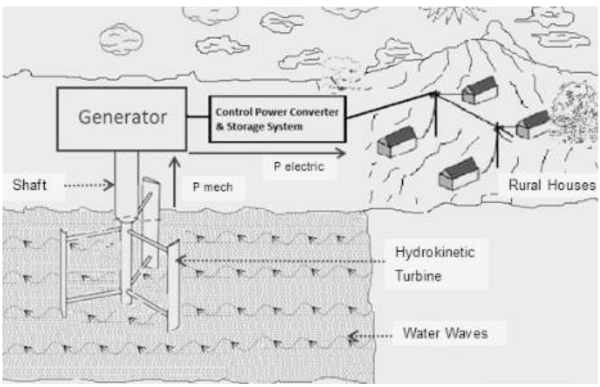


Fig. 1: Outline of off-grid hydrokinetic energy conversion system

## 1.5 Hydrokinetic operation and advantage compared to wind generation

Hydrokinetic technology shares lot of similarities with wind turbine systems in terms of physical operation principles, electrical hardware, and variable speed capability for optimal energy extraction [28]. The advantage is that the water is approximately 800 times denser than air, hence it extract enough energy even at low speed [29-32]. This simply implies that the amount of energy generated by a hydrokinetic turbine is much greater than that produced by a wind turbine of equal diameter. It can be installed in flow with water velocity ranging from 0.5 m/s and above [15]. There are many concepts for harnessing this energy, but turbine is being the most common and proven one. Similar to wind energy converters, the output power (watts) captured by hydrokinetic turbine is given by equation (1).

$$P_a = \frac{1}{2} \times A \times p \times V^3 \times C_p \qquad (1)$$

Where A is turbine area ($m^2$), ρ is the water density (1000 $kg/m^3$), V is the water current velocity (m/s) and Cp is the turbine power coefficient or efficiency = 16/27 = 0.593 (theoretical maximum power available). Similar to wind turbine, the power coefficient (Cp) denotes that the hydrokinetic turbines can only harness a fraction of the total kinetic power due to losses entailed. This coefficient is limited to 0.593 by the well-known Betz law [33 & 34]. But a small-scale river turbine has its own losses which will reduce the power coefficient to around 0.25. The upper limit is for highly efficient machines with low mechanical losses.

## 1.6 Research gap

There is a lack of studies demonstrating the technical and economic benefits of this proposed system. Furthermore, no mathematical model for the performance evaluation of the system has yet been developed. Hence, remote villagers and site owners (farmers) in the vicinity of such rivers are unable to utilise the water resource.

Based on the stated problem, the following sub-problems are identified:

- Sub-problem 1: Development of the mathematical model for performance evaluation of the proposed alternative system. This developed model will be applied in MATLAB / Simulink software.
- Sub-problem 2: Comparison of the proposed alternative system to grid-extension, diesel generator, solar, wind and traditional micro-hydro system in terms of cost-competiveness and environmental impact.
- Sub-problem 3: Practical application of the proposed alternative system to meet electrification needs of the selected rural community and to validate the developed mathematical model.

## 2. OBJECTIVES

The aim of this study is to demonstrate the viability of the proposed off-grid MHR system to rural residents not served by the grid and in close proximity to flowing water.

The objectives of this study are as follows:

- To develop a mathematical model.
- To simulate the proposed system using MATLAB/Simulink software as submitted to different solicitations such as varying water resources, load fluctuations, etc.
- To present economic and environmental analysis of the proposed system as compared to other possible rural electrification options in the study area.
- To be able to identify a potential site for application.
- To build and test a prototype of the proposed system in order to validate the simulation results.

## 3. HYPOTHESIS

The first hypothesis of the study will be the development of a mathematical model for the assessment of the proposed off-grid MHR system. The second hypothesis will be the use of the proposed off-grid MHR system as a cost-effective and sustainable electricity supply mean for remote rural residents in close proximity to flowing water and with no access to grid electricity.

## 4. REVIEW OF LITERATURES

Hydrokinetic technology is still in the development stage and there is a lack of application especially in rural areas with reasonable water resources. It has been noticed that most hydrokinetic literatures have concentrated mainly on large scale technologies such as waves, tides and ocean current applications. Currently, only a small portion of micro-hydrokinetic river technology has been exploited for rural electrification. This might be the main factor delaying the utilization of MHR technology in rural areas. The utilization of MHR technology presents a possibility of improving living standards of rural residents in an environmentally-friendly manner and at an affordable cost.

In this review, recent application and development studies based on micro-hydrokinetic river technology from rural electrification perspective have been discussed.

## 4.1 Hydrokinetic river turbines

Several hydrokinetic conversion concepts have been developed for river applications. Hydrokinetic turbines are the most widely used one. Hydrokinetic turbines are designed to generate electricity solely from the kinetic energy of running water. Vertical axis Darrieus, H-Darrieus or Helical turbine are appropriate to be used in cases where the water flow rate is relatively limited (i.e. rivers, manmade canals, dams, etc.) [25].

Anyi and Kirke [35] reviewed works involving small axial flow hydrokinetic turbines specifically for generating electrical power for off-grid remote communities and suggested improvements to overcome debris problem. Turbines mounted on pontoons or suspended using pivot arms from river banks or from jetties are reported able to produce about 1 kW to 2 kW of electrical power suitable for remote homes. A deflection device and system that uses rotor with swept-back blades were suggested to overcome debris problem. By making the system resistant to debris, efficient axial flow turbines could be used practically in tropical rivers.

Kirke [36] reviewed the recent developments in open flow current turbine design and explored some potential advantages of ducted or “diffuser-augmented” current turbines. Safety improvement, protection from weed growth, increased power output as well as the reduced turbine and gearbox size for a given power output were included in this review.

Van Arkel et al. [22] introduced a new type of kinetic hydropower generator, ideally suited to relatively small shallow rivers and channels. The design utilizes rectangular hydroplanes ('sails') moving around the device. The device extracts energy from a flow of water using an elongated vertical axis turbine, where a series of sails are mounted between two belts at the top and bottom of the device, rotating in the horizontal plane. The concept would be ideally suited to relatively shallow rivers and channels, because it can be designed to fill more of the channel's cross-sectional area than the circular rotor of a standard marine turbine or array of turbines.

Birjandi et al. [37] investigated the macro-turbulent flow structures interaction with vertical hydrokinetic river turbine. The results aimed to characterize flows in rivers as to improve their understanding in the impact of turbulent inflow structures on hydrokinetic power generation, and to contribute to the optimization of vertical and horizontal axis hydrokinetic turbines. Furthermore, power spectrum measurements provided data to improve the fatigue lifetime estimation of vertical turbines, as the scale and intensity of turbulent structures can play an important role.

Kirke [38] carried out some tests on several helical and straight blade Darrieus type cross flow hydrokinetic turbines with and without variable pitch, with and without slatted diffusers. Variable pitch has been suggested to increase starting torque and efficiency, ducts to increase power output and helical blades to produce smooth torque. These tests were performed at velocities ranging from less than 1m/s and up to 5m/s in Nerang River of Australia and Campbell River in Canada. These findings suggest that variable pitch cross flow on hydrokinetic technologies should be further investigated.

Goletcha et al. [39] studied the interaction among multiple Savonius turbines used for small-scale electricity generation in remote areas. This interaction was studied to avoid the power loss due to negative interaction between turbines. The interaction between two Savonius turbines arranged in a line was examined. The results concluded that two turbines placed at a separation gap of 8 performed independently without affecting the performance of each other.

### 4.2 Hydrokinetic river generators

Hydrokinetic turbines convert the kinetic energy of flowing water mass into mechanical energy. A device called generator will then convert that mechanical energy into useful electrical energy. Generally two widely used kinds of generators in wind and hydrokinetic turbine systems are permanent magnet synchronous generators and induction generators [23].

Permanent magnet synchronous generators (PMSG) have cornered the market in small scale hydro and hydrokinetic energy conversion systems due to its simplicity, high reliability, low noise and high power density [40]. Induction generators are available in types such as doubly-fed induction generators and squirrel cage induction generators [40-41]. The commonly used induction generators are squirrel cage rotor types since they are brushless. Induction generators need external excitation to be suitable for applications. This complexity can be avoided by using permanent magnet synchronous generator. Thomas, et al. [42] designed an efficient low speed permanent magnet generator to be utilized for low tidal current velocities, in the order of 1 m/s. At water current velocity of 1.5m/s generator yielded energy of 5kW.

### 4.3 Hydrokinetic river potential analysis and applications

The majority of people living in rural areas are very poor. Hence, a need exist to bring the most affordable rural electrification option in order to alleviate poverty. Among different renewable energy technologies, micro-hydrokinetic river is simple to design and can be easily installed and maintained by local population at low cost if installed in remote and rural areas. Few studies have been done to prove economic benefits of this technology.

Kunaifi [43] evaluated the most cost effective hybrid option by harnessing energy from a combination of river hydrokinetic power and different energy sources. Two options were recommended to meet the future electrical load in a typical Riau rural village. The first option was a hybrid power system comprised of a photovoltaic array, Darrieus hydrokinetic turbines (DHTs), a back-up diesel generator, a battery bank, and an inverter. The second option consisted of a diesel generator with biodiesel fuel only.

Kusakana and Vermaak [17] simulated the savings potential of Hydrokinetic power compared to Photovoltaic system, diesel generator and grid extension line by making use of the Hybrid Optimization Model for Electric Renewable (HOMER) simulation software. This study investigated the possibility of using and developing hydrokinetic power to extend the reliable, affordable and sustainable electricity supplies for rural, remote and isolated loads in rural residents of South Africa where reasonable water resource is available. This study did not entail the system modelling and practical application of this technology.

Kari Sornes [44] summarised the existing technologies within hydrokinetic water current turbines with a unit power output of about 0.5-5kW. The commercial market which existed in this hydrokinetic field and some previous experiences in rural areas were summarised. Discussion on performance analysis and modelling issues were beyond the scope of this work.

## 5. METHODOLOGY

To achieve the above mentioned objectives, the methodology is as follows:

### 5.1 System modelling

Mathematical model is developed to describe the performance of the proposed system. MATLAB/Simulink software will be used to apply the developed model and simulate the behaviour of proposed system under different solicitation (such varying water speed, varying electrical load, etc.). The proposed system will comprise of turbine, shaft, gearbox and a Permanent magnet generator. Hence, all mentioned system components will be modelled.

### 5.2 Selection of rural community

A rural community to be selected in this study is a relatively small population (e.g. two houses, three houses, etc.) without access to grid and in close proximity to permanent water flow. The electricity requirements of the selected rural community will be established through load forecast. This proposed system will supply the basic needs such as small domestic load (e.g. lighting, television, radio, portable fridge, etc.). Heavy consumption appliances such as stoves, heaters, air conditioners, etc. are excluded.

## 5.3 Site assessment

The potential site to be assessed must meet the following criteria:

- Must have permanent water flow.
- Must be in the vicinity of rural village (to avoid high distribution costs).
- Must not be in an unsuitable area (e.g. national parks, electrification field, etc.).

## 5.4 Power assessment

The potential power of the selected site will be assessed in order to verify the feasibility of the proposed system and be compared to the power demand needed. This assessment will be performed by measuring the flow velocity, depth, and width of the selected site through the use of float method, long-scaled stick, and stretching metal string, respectively.

## 5.5 Economic and Environmental analysis

Economic and environmental analysis of the proposed MHR system will be performed through the use of Hybrid Optimization Model for Electric Renewable (HOMER) software developed by the National Renewable Energy Laboratory (NREL) of the United State of America (USA). Net present value (NPV) and energy cost analysis of the proposed system will be simulated with the use of water resource data from the selected site, electrical load demand and system component costs as inputs to HOMER software; and then compared with those of other supply options such as grid extension, Solar PV, diesel generator and traditional hydropower system supplying the same electrical load. The results will also highlight the reduction of gas pollutant emissions achieved.

## 5.6 Experimental work

A small scale experimental prototype of the proposed MHR system will be built and applied in the selected site to verify the simulation results. This prototype might range between 1 to 4 kW depending on site characteristics (available potential power) and the load demand.

# 6. CONCLUSION

According to literature studies base on small scale hydrokinetic river system, it has been noticed that most studies concentrated exclusively on the suggestions and developments. There is a lack of studies demonstrating the practical application prototype for remote electrification. Hence a field performance test will be performed in this study. Secondly, no mathematical model has yet been developed to evaluate the performance of this proposed system. Hence, a mathematical model to be developed in this study will enable the researchers to evaluate the performance of the hydrokinetic system.

Thirdly, this study also intends to demonstrate the economic benefits of using hydrokinetic river resource by demonstrating its techno-economic benefits. This will be useful to researchers, site owners, investors, project developers, policy and decision makers who are responsible for critical screening and approval of rural electrification programmes by comparing the proposed system to other rural electrification options.

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